Development of an Automated Generation System for BWR Plant Startup

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One of the most complex core management tasks in support of BWR plant operation is the development of the startup procedure. Much working time and computer resources are spent on startup planning as it requires many survey calculations and the confirmation of many design parameters. An automated generation system has been developed to support the startup planning work with the goal of improving productivity and enhanced quality control. The system is composed of three modules. The confirmation of design parameters is performed by SIMULATE-3. Startup planning experience of engineers has been introduced into the system in order to reduce calculation time. The result of trial calculations was good and the system achieved a 60% reduction in the time an engineer would spend to perform the planning manually. Further improvements have been identified and will be implemented in order to achieve greater savings.

KEYWORDS: Startup Procedure, Automated System, SIMULATE-3

I. Objective of System Development

In recent years, the demand for cost savings in the electric power industry has been accelerating, particularly for nuclear power plants. Under such pressure, TEPCO SYSTEMS CORPORATION (TEPSYS), a provider of BWR in-core fuel management services, has been focusing on cost saving solutions which can be achieved via design automation.

TEPSYS has developed various automation systems to assist in core management tasks. One example is FINELOAD-3\(^1\), a loading pattern optimization system for boiling water reactors. Another example is an in-house documentation system for reload core design work. Both systems have been implemented and extensively applied to actual projects. They have significantly reduced costs through increased productivity and enhanced quality control.

Another important core management related task performed by TEPSYS is the planning of the reactor startup procedure following a refueling outage or in some cases an unplanned shutdown during operation. The startup procedure for a BWR core is fairly complex, requiring the confirmation of many design parameters and is very labor intensive, even for an experienced engineer. In addition, the outage period for nuclear power plants is becoming shorter in order to achieve greater operating efficiencies. Consequently, the time frame to perform this procedure as well as numerous other analyses prior to plant startup has become critical. For these reasons, an automated system that can develop a startup procedure in a short period of time is highly desirable.

Such a system is also significant from the perspective of quality control. By reducing human intervention, the possibility of error is also reduced. The time required for verification of design input and output can be significantly shortened as well.

II. General Start-Up Procedure

1. Objectives and Outputs

Briefly stated, the startup procedure is a process to bring the reactor core to full power conditions by gradually withdrawing control rods and increasing core flow, starting from zero power conditions.

The startup procedure is represented by the operating parameters, for example core power and flow, and control rod patterns at various time steps, from a zero power condition to full power rated conditions. In general, plant startup occurs when the core is “xenon free” and as reactor power increases and control rods are withdrawn, xenon will be constantly changing, requiring a detailed trace of core parameters as time progresses.

Figure 1 shows the change in core power versus time during startup. This is the typical BWR startup scenario planned by TEPSYS and it is devised to shorten the overall startup time. This figure is useful for evaluating the entire startup procedure. The most economical startup procedure is one which has minimum power loss between zero and full power conditions. This loss is represented by the gray shaded area in Fig. 1. In order to minimize this area, core power must be increased to the highest levels possible within the shortest amount of time.

The relationship between core power and core flow is represented by the power-flow map shown in Fig. 2. In this figure, vertical lines show the core power change resulting from control rod withdrawal, diagonal lines show the core power change as a result of core flow change, and horizontal lines show that core power is held constant while core flow changes.

These two figures are key outputs of the startup planning procedure. In addition, it is necessary to determine the control rod withdrawal sequence from zero power conditions.
Fig. 1  Power Curve During Startup Procedure

Fig. 2  Power-Flow Map
when all control rods are fully inserted to the final target rod pattern determined at the rated power condition. The target rod pattern was determined when the optimized core loading pattern was developed.

2. Design Criteria

As can be seen from Fig. 1, core power cannot be simply increased as there are other criteria that must be considered during the startup procedure.

One of these criteria is the operating area represented by the dotted lines in Fig. 2. This area is determined for each BWR plant type and depends on the performance of various plant equipment as well as plant safety restrictions. It must be confirmed that the core power and core flow selected for the startup procedure do not deviate from this operating area.

Other important criteria are thermal limits, that is linear heat generation rate (LHGR) and critical power ratio (CPR). Both thermal limits inform us about the local power intensity. In recent reload core designs developed by TEPSYS, LHGR easily approaches a limit value which was conservatively selected during the startup, but CPR doesn’t often approach the limit. LHGR indicates three-dimensional local power and it is sensitive to changes in control rod movements; therefore confirmation is needed for each movement. On the other hand, LHGR changes proportionally with core power as core flow is changed, so it is easy to predict the LHGR change under these conditions without detailed confirmation.

While LHGR is below the limit value, core power can be increased without restrictions by control rod withdrawal and/or increasing core flow. Once LHGR exceeds the limit value, restrictions are placed on those actions which can increase core power, that is, control rod withdrawal and increasing core flow. Core power is allowed to increase as long as the rate of increase of LHGR satisfies the design criteria. Consequently this will increase the overall startup time. Figure 3 shows LHGR versus time for a typical startup procedure. In this figure, LHGR has exceeded the limit value at around point F, and LHGR is only permitted to increase slowly after that point. It corresponds to the latter half of region 4 shown in Fig. 1.

3. Method of Startup Procedure

Before beginning the explanation of the automated startup procedure generation system, it is helpful to describe in greater detail the startup procedure based on Fig. 1 and Fig. 2. The startup procedure has been divided into four regions for the purpose of this explanation.

In region 1, core power increases from zero to about 50% power. The procedure for increasing the power in this region is fixed for each BWR plant by plant operations. However, the control rod pattern at point A differs for each reload core design. Since the power level is low, there are no restrictions due to thermal limits. The operating area shown in Fig. 2 is relatively wide, allowing for the unrestricted withdrawal of 50% of the control rods, with the remainder inserted in a checkerboard-like pattern.

In region 2, core power is increased from 50% to a high power level in a short time period. As shown in Fig. 2, the
power is increased primarily by control rod withdrawal until the power level approaches the operating region boundary (point A'). Usually, LHGR is below the limit value at A' and the power level is increased to point B by increasing core flow. It is obvious from Fig. 1 that the high power level achieved at B can significantly reduce power loss in regions 2 and 3. Moreover, the high power level accelerates the accumulation of xenon; consequently overall startup time can become shorter. For this reason, the power level at point B is very important. Since this power level is dependent on the LHGR (see Fig. 3), many control rod pattern calculations are performed in order to find one which achieves a high power level with LHGR at or below the limit value. On the other hand, LHGR may closely approach the limit value between points A and A' (see Fig. 3) so it is necessary to perform calculations at each rod withdrawal step.

In region 3 the power level is held constant for several hours while xenon accumulates in the core. It is important to select an appropriate time period for maintaining a constant power level as this affects the power loss in regions 3 and 4. If the time is inadequate, the power will violate the operating area at point D' (see Fig. 2) where the target pattern is established because the accumulated xenon will be insufficient to suppress local power. Even if the target pattern can be established within the operating area, the power level at point E may become low, resulting in a larger power loss in region 4. On the other hand, it is obvious that the power loss will also be large if the power level is held constant for an unnecessarily long period of time.

Since the core power will decrease with time as the xenon concentration increases, the power level is maintained with gradual control rod withdrawals and/or core flow adjustments. At first, the power is maintained by withdrawing control rods. The order of withdrawal is an important factor to minimize the overall startup time and many rod withdrawal scenarios are investigated in order to select the optimum rod withdrawal sequence. In region 3, LHGR is always close to the limit value (see Fig. 3), so it is necessary to confirm each step change, especially when control rods are withdrawn. When it becomes impossible to further withdraw control rods due to the LHGR limit value restriction, the power level is maintained by core flow adjustments. When core power is maintained in this manner, LHGR does not change drastically, but it is necessary to confirm that the flow stays within the operating area shown in Fig. 2.

In some cases, the holding time period is not satisfactory with the control rod pattern selected at point B. For some patterns, it becomes impossible to make further rod withdrawal changes or the core flow may exceed the operating area before a satisfactory holding period has been achieved. In this case, a new pattern must be tried.

In region 4, the power level is increased to rated power. The power level is decreased from point C to D by decreasing core flow for the sake of increasing the transient xenon, as this will allow the target pattern to be established more easily between points D and D'. The power level at point D is determined by the LHGR value; that is, LHGR must be sufficiently below the limit value at D in order to allow control rod withdrawal to reach point D'. LHGR must remain below the limit value at point D' so that the power level can be increased to point E by increasing core flow. The holding period from point E to F is fixed, and is established by plant operations. The rate at which core power level is increased from point F to G is restricted according to the allowed rate of increase of LHGR. The power loss during this period is not insignificant and the optimum rate of increasing power level must be determined from many survey calculations. Beyond region 4, core flow adjustments are needed until xenon equilibrium conditions are reached. However there is no associated power loss and the startup procedure is completed at point G.

III. Automatic Generation System

As described in the previous section, planning the startup procedure is a very complex task, requiring much effort and many calculations. To reduce the time needed to perform startup planning, many of the survey calculations have been automated in a new system.

![Fig.4 Relation of Previous Patterns and Subject Pattern](image)
This system is constructed in three modules. Calculations to confirm core conditions and thermal limits are performed by the three-dimensional reactor analysis code SIMULATE-3.2)

1. Module M1
The startup procedure corresponding to region 2 is determined by module M1. The core conditions and control rod pattern at point A are provided as boundary conditions with the goal of establishing the conditions and rod pattern corresponding to point A'.

In the case of manual planning, after a suitable control rod pattern is selected at point A', the rod withdrawal sequence is investigated between point A to A'. An acceptable withdrawal sequence cannot always be found, in which case the pattern at A' must be revised.

By using module M1, the withdrawal sequence has already been determined when the control rod pattern is selected based on the results at point A', since calculations were explicitly performed at each rod withdrawal step from the starting point A.

All of the rod patterns at each withdrawal step are explicitly calculated in order to establish the pattern at point A'. The results of all calculations are stored in a data base which is then utilized to make a judgment for future pattern selection. Figure 4 shows an example of rod patterns displayed in quarter core format. The number 0 indicates that the control rod is fully inserted while 48 indicates a fully withdrawn rod, but for clarity a blank has been shown. The minimum unit in which a control rod can be moved is 2 and only an even number position is permitted. Patterns 1 through 5 are all previous patterns existing in the rod withdrawal sequence prior to achieving pattern 6. If any of these five patterns do not satisfy the criteria, then pattern 6 would not be calculated since the withdrawal sequence could not be confirmed by a previous pattern. Although the calculation of pattern 6 is not performed, the fact that it is a “failed” pattern is recorded in the data base. This method of recording all withdrawal sequence attempts in a data base is a means of decreasing the overall number of calculations. The data base method becomes more and more effective as control rod withdrawal proceeds.
After the calculations are finished for all patterns, the results that satisfy the criteria are sorted in order of core power at point A'. In the case where two or more patterns have the same core power, priority is given to the pattern with the lower LHGR, as power must subsequently be raised further from points A' to B.

2. Module M2

The objectives of this module are to establish the method of holding the core power constant prior to setting the final target pattern at point E and to do so in the shortest possible time period. The module M2 is divided into two parts. The core conditions and control rod pattern at point B are provided as boundary conditions.

The first part of the module performs calculations in which control rods are withdrawn to maintain power level. Figure 5 shows a diagram of this process. The pattern at point B1 is first established given the rod pattern from the previous time step at point B. All rod patterns are explicitly calculated and the results stored in the M2 data base. From among the list of patterns which satisfy the criteria, the pattern which has the lowest control rod density, that is, the pattern which has the most control rods withdrawn, is selected as the pattern at point B1. In the case where there are two or more patterns having the same control rod density, the pattern in which the higher ranked control rods are more fully withdrawn has priority. The control rod ranking is established based on engineering judgment and past startup experience, both of which are valuable for determining an efficient startup procedure. With the rod pattern at point B1 established based on the method just described, the pattern at the next time step, at point B2 in Fig. 5, must be determined. Calculations using other patterns which were not selected at point B1 are not performed in order to reduce analysis time. This procedure is repeated until control rods can no longer be withdrawn. The core conditions and rod pattern are saved. The time step between calculation points depends on the degree of detail needed by the user in determining the minimum time period to maintain a constant core power level.

When the control rods can no longer be withdrawn, the second part of the module continues the calculations from previously saved points, holding the power level constant while adjusting core flow in order to successfully reach the target pattern at point E. Figure 6 shows this process. Let us first assume that B1 equals point C, and then calculate the core conditions from point C to D'. If the results at point D' satisfy the criteria, then the time period between B and C (assumed as B1) is the minimum time period for the startup procedure. If the result at D' does not satisfy the criteria, then the time period at which power is held constant must be lengthened. In Fig. 6, B11 is now assumed to be point C and the core conditions are recalculated from this new point C to D'. This procedure is repeated until the criteria at point D' can be satisfied and the minimum time period for maintaining constant core power can then be determined, shown in Fig. 6 as point B1'. The minimum time period and the core conditions at point B1', that is the results of module M2, are saved for use in module M3.

This procedure is performed for each of the saved points, that is, B1, B2, B3 and so on.

Fig.6  Holding Power with Core Flow Change

3. Module M3

The startup procedure from the point where the time period to hold core power constant ends, that is point E, to point G is established by module M3.

Although the minimum time period determined in module M2 is the required time to establish the target rod pattern at point E, it does not always result in the minimum total power loss. In the case where the holding time period is extended, the total power loss may actually become smaller compared to the power loss obtained by the module M2 result. This is because a longer time period may permit a higher core power at point E.

This procedure, like the second part of module M2, is performed from previously saved points, such as point B1', to point G. If the power loss becomes larger than the loss calculated for the previous holding time, then the most suitable holding time is the previous holding time.

This procedure is performed for each of the saved points.
4. Conjunction of Modules

The module M3 is connected to the module M2, while the module M1 is used independently. The most suitable startup procedure from points B to G can be obtained once the pattern is fixed at point B.

Presently users select some pattern results from module M1 and calculate point B manually from point A', then input this pattern to module M2.

IV. Results

This automated system was applied to a BWR5 with a thermal power of 3293 MW and a gross electric power output of 1100 MW. This plant contains 764 fuel assemblies and 185 control rods. Calculations were performed using a SUN Enterprise 420R (450 Mhz).

Figure 7 shows the initial rod pattern at point A for module M1 and the corresponding notch map which defines the maximum movement per withdrawal step for each control rod. One notch is about 3 inches. The control rods represented by blanks in the notch map are not restricted to fixed notch movements. If all control rod movement was governed by the notch map and the minimum movement set to 2, then calculations could be performed for all possible patterns. In this case, the calculation time would become enormous. Notch values can be set to a value larger than 2 without significantly affecting the results. Because the rod worth of peripheral control rods is smaller than that of centrally located control rods, the maximum notch step was set to 24. For this study, the calculation time was 60 hours.

Figure 8 shows an output edit of module M1. In the figure, the patterns and conditions are shown in the order described in section III. On the right side of this edit, the limit values and judgment regarding the results are shown.

Fig.7 Trial Case - Initial Condition

Fig.8 Result of Module M1
One of the patterns which was manually adjusted from the results obtained from module M1 was transferred to module M2/M3, and the most suitable startup procedure from points B to G was calculated. In the module M2/M3, the notch movement for all control rods was set to the minimum unit of 2 because the rod movement within region 3 is rather small. Consequently, the calculation time within the holding period with core flow adjustment was 4 hours, the calculation time during the holding period with control rod withdrawal was 14 hours, and the total time period from point B to point G was 45 hours. As it usually takes about five days to manually perform the startup procedure by an experienced engineer, a 60% reduction in the applied working time by the automated system is a significant savings.

V. Improvements of System

Based on the trial application of these modules, various improvements became obvious. The method to link module M1 to the other modules must be carefully considered. As it usually takes about five days to manually perform the startup procedure by an experienced engineer, a 60% reduction in the applied working time by the automated system is a significant savings.
the results were sorted in order of core power at point A', similar patterns tended to be gathered together. However, if a startup plan cannot be successfully established for a rod pattern at point B in module M2, a startup plan will also not be possible for similar patterns. If the patterns are then automatically transferred from module M1 to module M2, the calculation time can become enormous before a suitable startup plan is obtained. This problem must be solved before the modules are connected.

Another problem is the overall calculation time of module M1. The rod patterns which are evaluated are subject to restrictions, for example control rod notch withdrawal is based on the user’s previous startup experiences. The module M1 applies the standard startup procedure shown in Fig. 1 and Fig. 2. To be able to investigate various alternate procedures, however, the technique of parallel computing must be considered.

Comparison to manually generated startup plans indicate that other improvements should be implemented in module M2. Core power can be increased slightly during the holding period between points B and C when there is sufficient margin to the LHGR limit value. At present, however, making an improvement to the rod pattern or core power level during this holding period means that the user must rerun module M2.

As these various improvements are added to the modules, the startup planning procedures will approach the level achieved by an experienced engineer in far less time.

VI. Conclusion
The basic startup planning modules have been developed and the trial application went well. They have been used for actual planning of basic startup procedures and for various survey calculations.

The automated system reduced the applied working time for performing the startup planning manually by about 60%, considering the work scope covered by the system.

Continued improvements to the system must be made to more fully automate the startup planning procedure. The development of an associated documentation system for the startup procedure will also be considered. Linkage to the stability analysis system which has already been developed by TEPSYS will also be investigated.